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Article

Performance, economics and sustainability of small wind energy conversion systems: an analysis using standard exergy and extended exergy accounting methods

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ABSTRACT

This study presents the performance, economics and sustainability indicators of wind energy conversion systems (WECS) using standard exergy and extended exergy accounting (EEA) methods. The objective was to generate operational, sustainability and economic data for various wind locations in Nigeria for different small WECS configurations. The data generated will inform investment and policy development as Nigeria transitions to cleaner energy sources. Results indicate that exergy destruction (ExD), physical exergy (ExPH) and exergy efficiency vary significantly across locations and WECS specifications. The lowest ExD values, observed with the Bergey XL.1 WECS, ranged from 1.351×10^6 to 5.67×10^6 MJ. Standard exergy efficiency fluctuated between 2.88 % and 5.97 %, with sustainability indicators reflecting moderate values. From the EEA breakdown, the maximum variation in physical exergy reached 4.97×10^7 MJ. In contrast, maximum efficiency was 2.99%, demonstrating an efficiency gap between locations and WECS between 0.45% and 29.3%. The low values based on EAA are attributed to excluding externalities in conventional methods. Cost per kW also varied across locations, with payback periods ranging from 3 to 5.7 years. The EEA method effectively provided realistic data to guide investment and policy decisions.

1. Introduction

Energy plays a crucial role in driving social and economic progress, as it is essential for producing and transporting necessities like food and water [1]. Due to growing energy consumption, environmental concerns, and rising energy generation costs, developing economies are increasingly adopting eco-friendly power generation technologies and efficient energy systems. Renewable energy, particularly wind energy, supports environmental sustainability by providing sustainable and renewable energy sources [2]. Wind energy, captured through wind turbines, has become a promising sustainable power source. In recent decades, population and economic growth have spurred global demand for wind energy [3]. If the global wind energy capacity, currently at 837 GW, continues to grow at 6.6% annually, it is projected that about 1.2 billion tons of CO_2 could be saved each year. In 2021, the United States and China increased their installed wind turbine capacities by 8.203 GW and 23.328 GW, respectively [4]. Over the same period, global wind power capacity grew by nearly 12.5%. Due to the growing integration of wind energy into electrical grids, research into wind energy has gained significant attention. Studies have examined wind potential in various locations worldwide. For example, Sunny et al. [5] studied wind speed and power generation characteristics in different Lithuanian regions, developing a mathematical framework to approximate their scale and form. Ayodele et al. [6] assessed wind energy potential in Antarctica's Vesleskarvet over eleven years, selecting wind turbines with rated powers ranging from 10 kW to 165 kW for simulation. Additionally, wind potential was studied in two Moroccan locations, Nouri et al. [7] and SEDM [3], and seven places in Nigeria's Niger Delta where wind turbines were assessed for their energy output Muyiwa et al. [8]. However, wind energy generation can fluctuate annually, limiting its ability to produce consistent power year-round [9].

To ensure the most cost-effective and environmentally responsible power generation methods, comparing the sustainability of renewable energy sources with traditional ones is crucial. The latter is achieved by using advanced thermodynamic techniques like exergy assessments. Exergy, or energy quality, represents the maximum usable work obtainable from a thermodynamic system when it reaches equilibrium with its surroundings. Exergy analysis is increasingly used to evaluate and optimize the performance of both renewable and nonrenewable energy systems [10]. Examples include wind turbines [11], gasification of biomass for hydrogen production [12], and other renewable energy systems like anaerobic digestion [13]. Exergy analysis can help design and improve various energy systems by incorporating mass conservation and the second law of thermodynamics. However, standard exergy analysis is insufficient in assessing externalities, such as labor, capita, and environmental impacts. Extended Exergy Accounting (EEA) addresses this gap by incorporating these externalities into sustainability evaluations. EEA's advantage lies in its ability to quantify non-energy externalities and evaluate energy systems comprehensively. It has gained significant traction in assessing energy systems' sustainability and productivity across various sectors. For instance, Ertesvåg [14] used EEA to examine Norway's energy sector, and Ptasinski et al. [15] applied it to evaluate the Dutch energy sector's performance. Other studies have used EEA to assess the sustainability of projects such as biogas systems in rural China (Chen and Feng [16]) and the Turkish transportation sector [17]. Although EEA has been extensively applied in various industrial and social sectors, its use in evaluating large-scale renewable energy systems, like wind power, remains limited. A study by Aghbashlo et al. [18] used EEA to assess the thermodynamic performance of an industrial-scale wind power system, comparing standard exergy and EEA methodologies. The study found 63.82% and 15.76% efficiencies for standard exergy and EEA methods, respectively. However, this research focused on a specific wind turbine type and location, prompting the need for a broader analysis. The current study seeks to extend the application of EEA by evaluating the performance and environmental sustainability of small wind energy conversion systems (WECS) across different locations and capacities. It will consider a range of externalities, including labor and capital, and conduct sensitivity analyses on variables such as wind velocity and kinetic energy flow. The objective is to provide a more holistic view of WECS sustainability by accounting for socio-economic factors and site-specific conditions.

The results will offer valuable insights for decision-making in wind energy investments, helping to forecast returns on investment and payback periods, which are critical for assessing wind energy projects' viability and optimal locations.

2. Methods

2.1 Description of study locations

This study focuses on six towns in Cross River State, Nigeria: Akamkpa, Obubra, Ikom, Ogoja, Boki and Obudu, which are emerging as economic hubs due to the Export Processing Zone, tourism, and a Mega Business Resort. Wind data from the Nigeria Meteorological Station (NIMET) in Calabar (2014-2023) at 10 meters was analyzed. Only average wind speeds were used, and calculations for wind power density and other characteristics confirmed the initial assumption of sufficient wind capacity for various applications and commercial purposes. Further location details are presented in Table 1.

2.2 Wind characteristic equations

The Weibull distribution function (WDF) is adopted to describe wind speed distribution in the considered locations. The two-parameter common form of the Weibull distribution probability function and the corresponding cumulative probability function are expressed mathematically in Eq (1) and Eq (2) [20].

$$f_{(v)} = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{1}$$

$$F_{(v)} = 1 - exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{2}$$

Where f(v) represent the possibility of observing wind speed (v), k the dimensionless shape parameter, c the Weibull scale parameter (m/s), and F(v) the cumulative probability function of the observing wind speed (WS) (v). The Weibull shape factor of a specific wind site shows how peaked the wind distribution is and also typifies the wind potential of the location. In contrast, the scale parameter shows how windy a wind location is. The wind power density, wind energy density, and annual energy are expressed in Khchine and Sriti [21]. The general exergy balance for a control volume in a steady state, neglecting potential, kinetic, and electrical energy, is defined as in Abam et al. [22] and Ozlu and Dincer [23].

$$\dot{Ex}_{dest} = \sum_k \left(1 - \frac{T_0}{T_k}\right)\dot{Q}_k - \dot{W}_{cv} + \sum_i\left(n_i\dot{Ex}_i\right) - \sum_e\left(n_e\dot{Ex}_e\right) \tag{3}$$

Table 1. Description of study locations OVC [19]

City	Location indicator	Latitude (degrees)	Longitude (degrees)	Population	Land area ($\mathbf{km^2}$)	Elevation (m)
Ogoja	OGP1	6.65^oN	8.70^oE	171,901	972	419
Ikom	IKP2	5.95^oN	8.78^oE	162,383	1961	400
Boki	BKP3	6.25^oN	9.06^oE	186,611	3000	666
Akamkpa	AKP4	8.52^oN	5.42^oE	151,125	5003	380
Obudu	OBUP5	6.67^oN	9.16^oE	161,157	415.6	570
Obubra	OBRP6	6.08^oN	8.32^oE	172,444	1115	364

The exergy analysis of WT is given by Patel [24] and Aghbashlo et al. [18].

$$Ex_{kin,in} - Ex_{kin,out} - Ex_{gen} - Ex_{des} = 0 \quad (4)$$

Where $Ex_{kin,in}$ is kinetic exergy inflow, $Ex_{kin,out}$ is the kinetic exergy outflow, Ex_{gen} is the generated energy by the turbine. The standard exergy efficiency can be computed [18] as:

$$\varphi_{ex} = \frac{E_{gen}}{Ex_{kin,in} - Ex_{kin,out}} \quad (5)$$

The exergy analysis and balances based on the EEA theory for the WT system are presented in Rocco et al. [25].

$$Ex_M + Ex_{PHY} + EE_C + EE_L + EE_{ENV} - Ex_{GEN} - Ex_{DEST} = 0 \quad (6)$$

$$Ex_{PHY} = Ex_{kin,in} - Ex_{kin,out} \quad (7)$$

Where Ex_M, is the exergy content of the material, Ex_{PHY} is the physical exergy, EE_C, is the equivalent of an extended exergy influx of capital, including operation & maintenance and insurance costs. EE_L and EE_{ENV} are equivalent to extended exergy content (EEEC) for labor and environment. Furthermore, EEEC of labor influx or inflow into the system and other factors are described in Seckin [26].

The equivalent extended exergy influx of the capital, operation, maintenance, and insurance cost is represented as:

$$EE_C = EE_K + EE_{O\&M} + EE_{ins} = (C_K + C_{O\&M} + C_{ins}) \times ee_c \quad (8)$$

Where C_K, $C_{O\&M}$ and C_{ins} indicates the cost of investment in the WT plant, operation, maintenance, and insurance.

The plant efficiency based on the EEA methodology is as follows:

$$\psi_{EEA} = \frac{Ex_{gen}}{Ex_{PHY} + EE_L + EE_K + EE_{O\&M} + EE_{ins}} \quad (9)$$

The sustainability index based on extended exergy is presented in Eq (10), while the other sustainability indicators based on the standard exergy method are presented in Table 2.

$$S_{EEA} = \frac{1}{1 - \psi_{EEA}} \quad (10)$$

3. Results and discussion

3.1 Locations wind speeds and parameters

The minimum wind speeds (WSP) in March are 3.53 m/s (AKP4), 3.90 m/s (OBRP6), and 3.89 m/s (IKP2), while the minimum wind power (WP) occurs in April, August, and February at OGP1 (4.56 m/s), OBUP5 (5.63 m/s), and BKP3 (4.7 m/s), respectively. None of the locations have WSPs below 3 m/s, suggesting potential for small-scale wind power projects.

The Wind Distribution Function (WDF) shows peak distribution at higher wind speeds and skewness toward lower speeds below 2 m/s Figure 1. Annual wind speeds are 4.12 m/s (OGP1), 3.38 m/s (IKP2), 5.3 m/s (BKP3), 4.0 m/s (AKP4), 4.89 m/s (OBUP5), and 3.42 m/s (OBRP6). The locations' monthly and annual wind power density (PD) range from 6.8 to 102.90 W/m^2 and 4.49 to 85.58 kWh/m^2, with yearly values between 48.31–85.58 W/m^2/year and 151.50–747.39 kWh/m^2/year. AKP4 and OBUP5 have the highest PD and ED, while OBRP6, OGP1, and IKP2 have the lowest. According to the Pacific Northwest Laboratory (PNL), all locations fall under class 1 wind resources [31].

Table 2. Sustainability indicators

S/No	Equation	Sustainability indicator	Equation number	Reference
1	$ESI = \frac{1}{1-\psi_{Ex}}$	Exergetic sustainability index	38	Sciubba [27]
2	$LOP = \frac{Ex_{LOSS}}{Ex_{out}}$	Lack of productivity	39	Chowdhury [28]
3	$WER = \frac{Ex_{LOSS}}{Ex_{in}}$	Waste exergy ratio	40	Abam et al. [29]
4	$EEE = \frac{WER}{\psi_{Ex}}$	Environmental effect factor	41	Abam et al. [29, 30]

3.2 Selection of WECS and performance outputs

Small-size WECSs (2.5 to 10 kW) were assessed for energy yield across different locations (Table 3) Shafiqu and Ahmet [32]. Monthly yields ranged from 56.79 to 24,524.26 kWh, and annual yields from 1,458.99 to 43,921.82 kWh (Figure 2). The highest performance was observed in the BKP3 location with Bergey Excel 10 kW, followed by Proven 2.5 kW and Skystream-3.7 kW. Capacity factors ranged from 5.03% to 50.13%, with the best performance at BKP3, OBRP6, and AKP2. Proven 2.5 kW and Bergey Excel 10 kW performed best across all locations.

3.3 Sensitivity analysis of standard exergy with upstream velocity

Figure 3 presents the aggregate energy generated (AEG), upstream velocity (USV), downstream velocity (DSV), exergy destruction (ExD), and physical exergy (PEx) vary across locations and depend on the WECS. The Bergey XL.1 had the lowest ExD (1.351×106 to 5.67×106 MJ), with exergy efficiency ranging from 2.88% to 5.97%. AKP4 showed the best performance with a maximum exergy efficiency of 5.97%.

Table 3. Technical specifications of selected wind turbines [33-39]

Turbines	Rated power (kW)	Rotor diameter (m)	Cut-in-speed (m/s)	Rated speed (m/s)	Swept Area (m^2)	Turbine cost (US$)
Bergey XL. 1	1.0	2.5	2.0	11	4.91	4864.86
Proven- 2.5 Kw	2.5	3.5	2.5	11	9.63	9705.96
Skystream -3.7 kW	1.8	3.7	3.0	11	10.76	6962.00
Southwest Whisper 500	7.5	4.5	3.5	11	15.91	9444.75
Bergey Excel 10 kW	10	6.7	3.0	13	35.27	55353.2

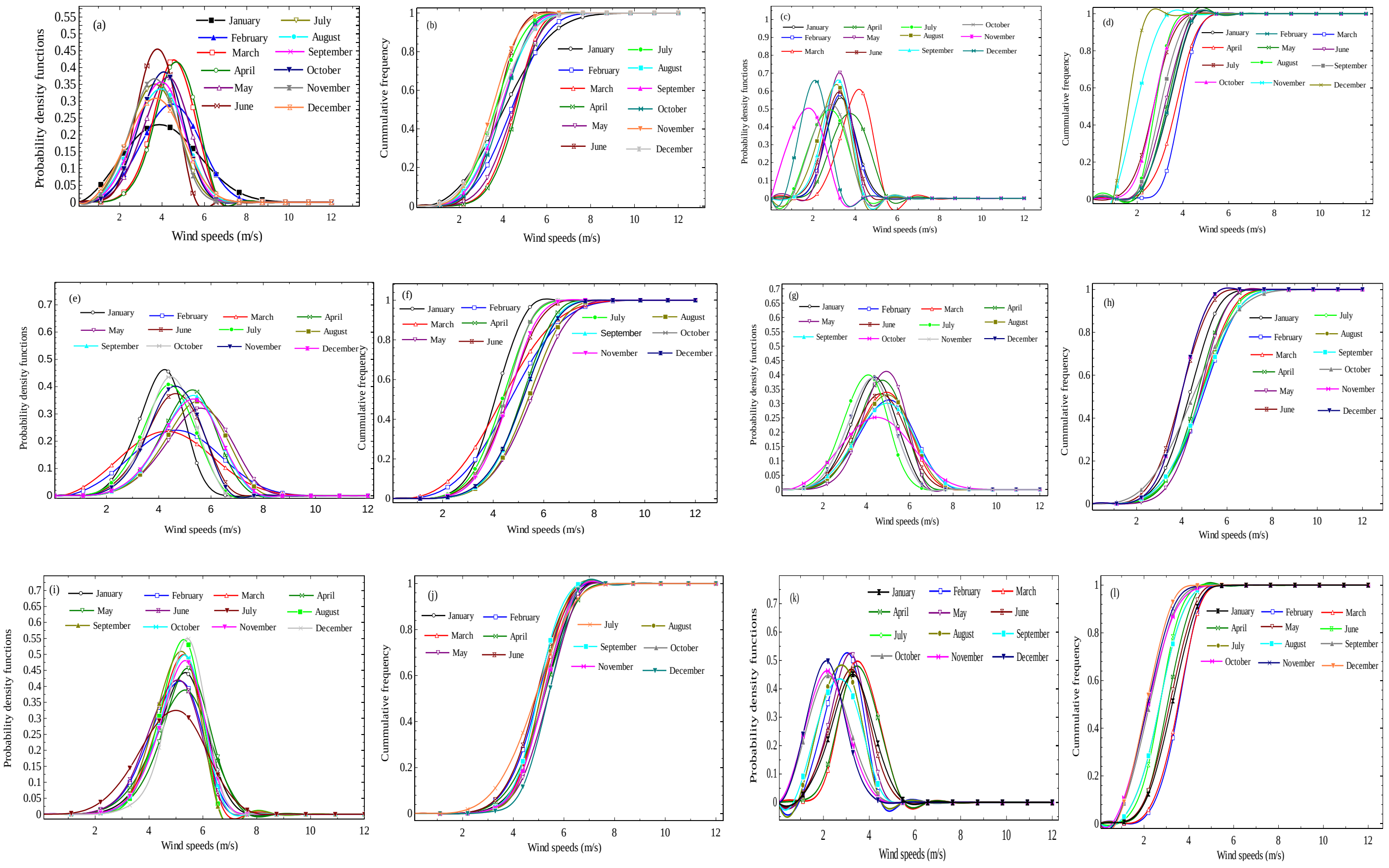
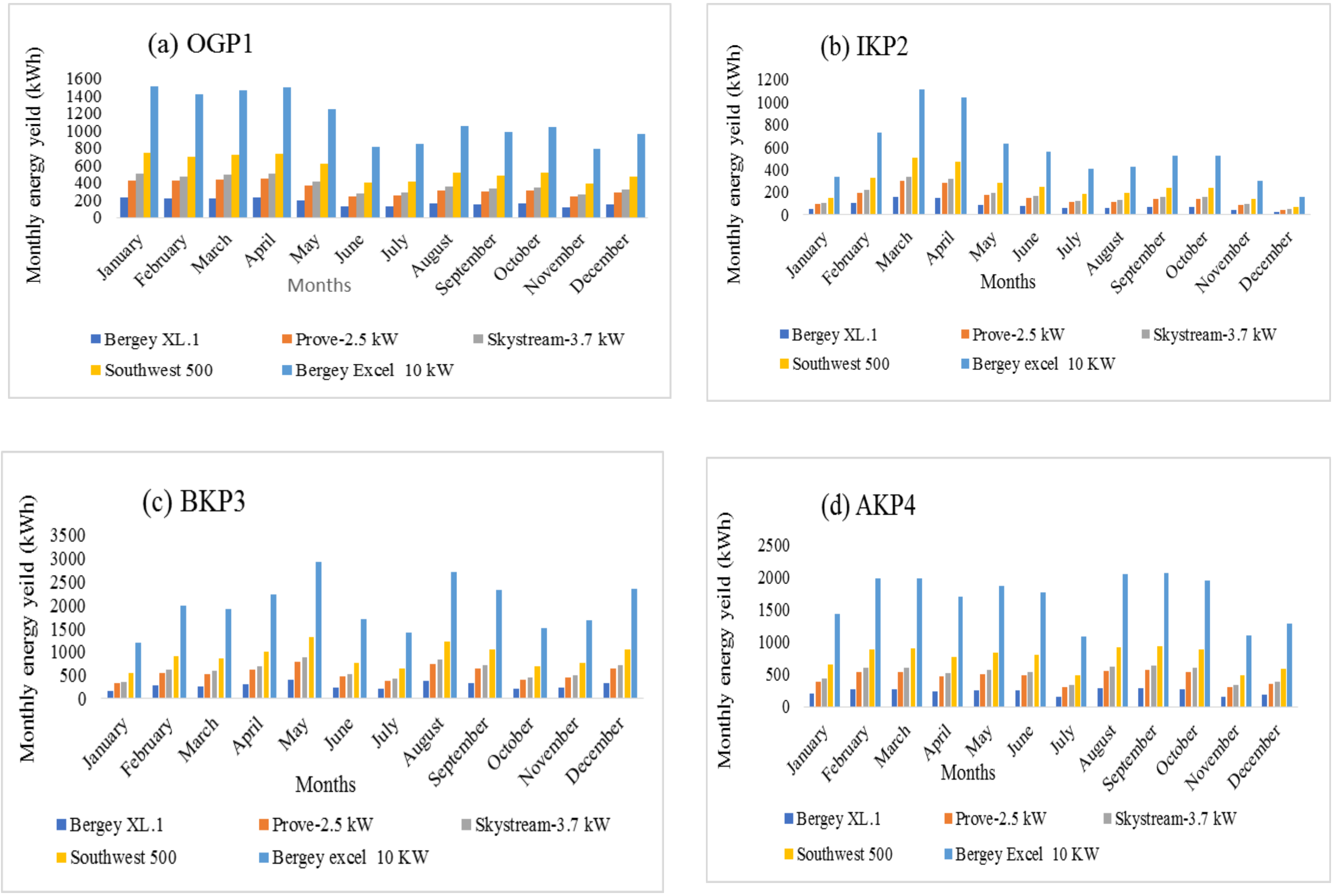


Figure 1. Monthly WSP probability and cumulative density distribution for the locations (a-b) OGP1, (c-d) IKP2, (e-f) BKP3, (g-h) AKP4, (i-j) OBUP5, (k-l) OBRP6



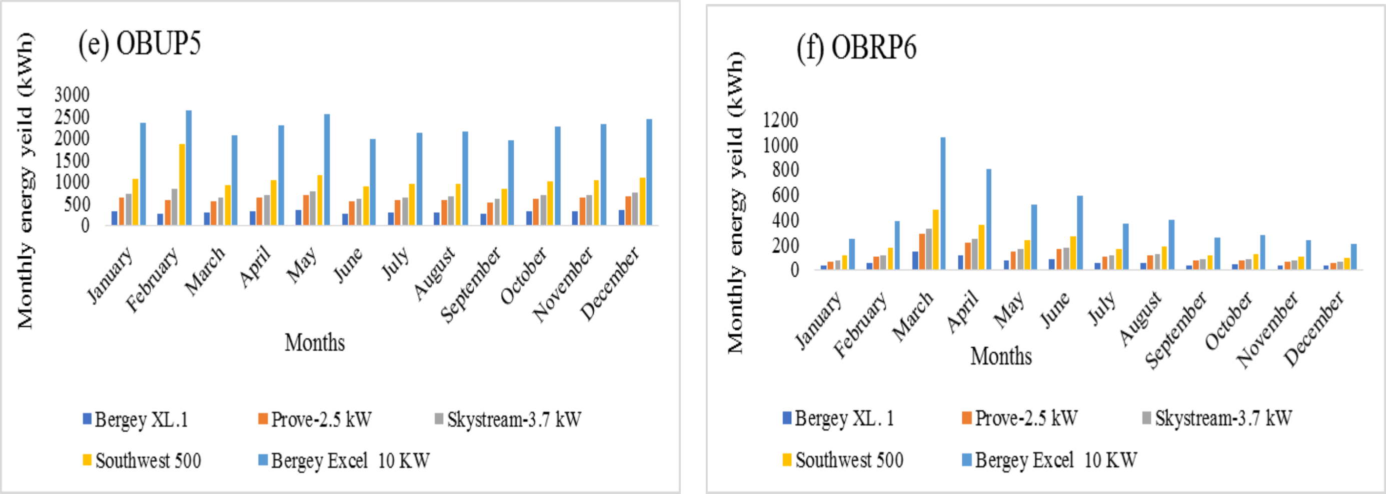


Figure 2. Monthly and annual energy yield from selected WECSs for the locations (a) OGP1,(b) IKP2, (c) BKP3, (d) AKP4, (e) OBUP5, (f) OBRP

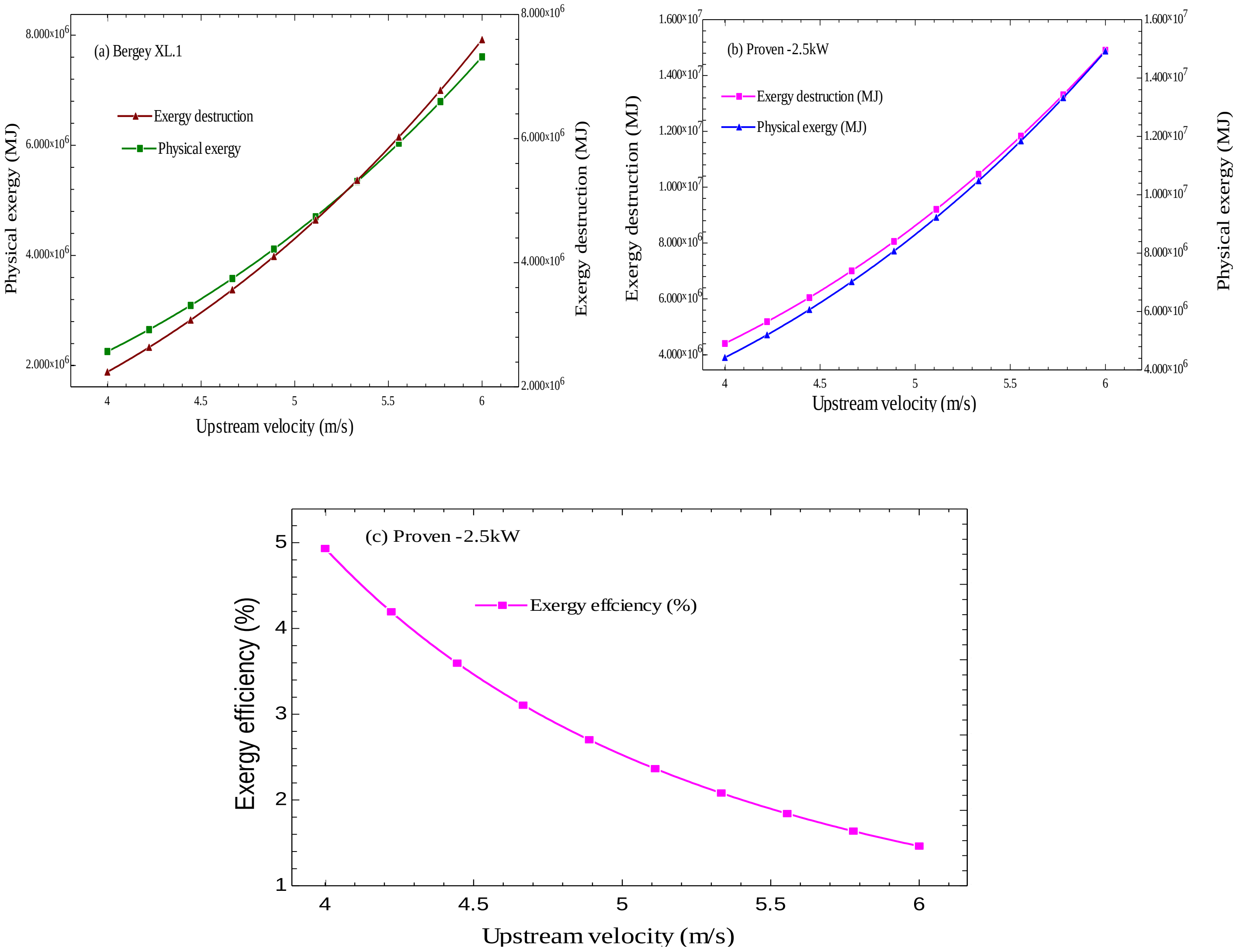


Figure 3. Effect of USV on exergetic parameters for OGP1 location using Bergey XL.1 and Proven-2.5 kW

ExD differences at AKP4 were about 4% between Proven-2.5 kW and Skystream-3.7 kW WECS. ExD and PEx increase as USV rises, with ExPH increasing by 4% and ExD by 0.45% per 1 m/s USV increase. Exergy efficiency decreases at higher USV (4.0–6.0 m/s) because net kinetic exergy increases more than electrical exergy. These findings highlight the importance of site-specific USV in optimizing WECS performance.

3.4 Performance and sustainability indicators of WECS

Figure 4 presents exergy-based sustainability metrics for different WECS at the OGP1 location, chosen for its representative performance trends, calculated from [40]. The study evaluates the Exergetic Sustainability Index (ESI), Waste Exergy Ratio (WER), Lack of Productivity (LOP), and Environmental Effect Factor (EEE). As seen in Figure 4a, the Bergey XL.1 shows increases in ESI (70.37%) and WER (9.09%) with a 33% rise in USV, suggesting better air mass flow conversion. Despite a slight WER increase, ExD remains low, reducing total exergy loss. Figure 4a to 4e show similar trends across systems, with Proven-2.5 kW and Skystream-3.7 kW exhibiting ESI increases of 46% and 52%, respectively, within the USV range of 4.0 to 6.0 m/s. However, LOP and EEE decline for all WECS. Ecological factors, such as site elevation, humidity, and particulates, also impact WECS performance. These ecological characteristics vary by location and play a crucial role in the performance of WECS.

3.5 Results from extended exergy accounting techniques

The exergetic equivalent of labour (ee_L) and capital (ee_C) are presented in Figure 5. The ee_L measures precisely how efficiently human labour or efforts transform quality energy (exergy) into useful productivity while ee_L measures the degree of energy quality and efficiency associated with capital goods, comprising productivity operation and maintenance. In the analysis, the HDI for Nigeria was 0.548 INR [41] and the HDI_0 for primitive society was 0.055 [18]. The number of inhabitants N_h was based on the population size of that particular location, as presented in Table 1. The cumulative number of working hours was determined based on the Nigeria setting, and the national wages salary was used as that in [40] for Nigeria. The results show that the ee_L vary from 43.36 MJ to 65.04 MJ, with BKP3 (Boki) having the largest ee_L followed by locations OBRP6, OBUP5, OGP1, IKP2, AKP4 with values indicate in Fig.6 respectively. Similarly, the values of ee_C vary from 64.88 MJ/$ to 80.11 MJ/$. BKP3, OBRP6 and OGP1 has the highiest ee_C of 80.11MJ/$, 74.03MJ/$ and 72.2MJ/$ in that manner. The results also show that as ee_L increase, ee_C also increases Figure 6. A large population can increase the overall quantity of human labor. If this labor is used effectively, it can lead to more productive output. However, the overall exergetic equivalent of labor is also determined by its quality and efficiency in consuming energy. Fig 6 indicates that an increase in N_h there is a corresponding increase in ee_L as well as ee_C. For a 1 MJ/h increase in the exergetic equivalent of labor, the ee_C in terms of productivity increases by about 0.68 %. These indices vary for locations and regions and are critical indicators for project managers and engineers to make meaningful decisions to improve capital output, reduce downtime, and maximize profit.

3.6 Equivalent extended exergy cost of labor and capital

The extended exergy cost of labor presents an all-inclusive assessment of the total energy consumption related to labor from an economic perspective. It includes all labor-related indirect energy overheads, such as facility, equipment, and administration. Similarly, the extended exergy cost of capital is the overall exergy costs for acquiring, maintaining, and operating capital assets. It includes the energy costs for creating the asset and any other indirect exergy costs related to its use. The economic parameters of the WECS and investment are first determined in determining the extended exergy cost of labor and capital. The initial turbine cost, initial cost of installation, capital influx in the year 2024, and operation and maintenance (O&M) are all presented in Table 4. The plant's lifetime was assumed to be 20 years, and interest rates for Nigeria in 2024 were taken at 26.66 %. The initial cost of installation and initial investment cost (transportation, custom fees, and installation were kept at 30 % of the turbine cost, while operation and maintenance were kept at 20 %. The capital influx for 2024 was calculated from [41], with a plant recovery factor (CRF) of 0.26. The capital influx (CI) was highest at US$19573 with Bergey Excel 10 kW, followed by Proven-2.5 kW and Southwest 500 with CI of US$3432 and US$ 3340, respectively.

Table 4. Economic parameters of WECS

WECS	Turbine cost (US$)	Initial cost of installation (US$)	Capital influx year 2024 (US$)	O &M (US$)
Bergey XL.1	4864.86	6616	1720	973
Proven-2.5 kW	9705.96	13200	3432	1941
Skystream-3.7 kW	6962.00	9468	2462	1392
Southwest 500	9444.75	12845	3340	1889
Bergey Excel 10kW	55353.2	75280	19573	11071

3.7 Economic of investment in the specific locations and WECS

In analyzing the economics of investment of the selected WECS in the respective locations, the cost of energy and the capacitor factor are determined for each WECS. The study adopted the methods available in ref [42, 43]. The present worth achieved for n number of years by discounting the cost of operations and maintenance, C_{om} to the first year for i interest rate is expressed as:

$$PV(C_{om})_{1-n} = C_{iv}\left[\frac{(1+i)^n-1}{i(1+i)^n}\right] \quad (11)$$

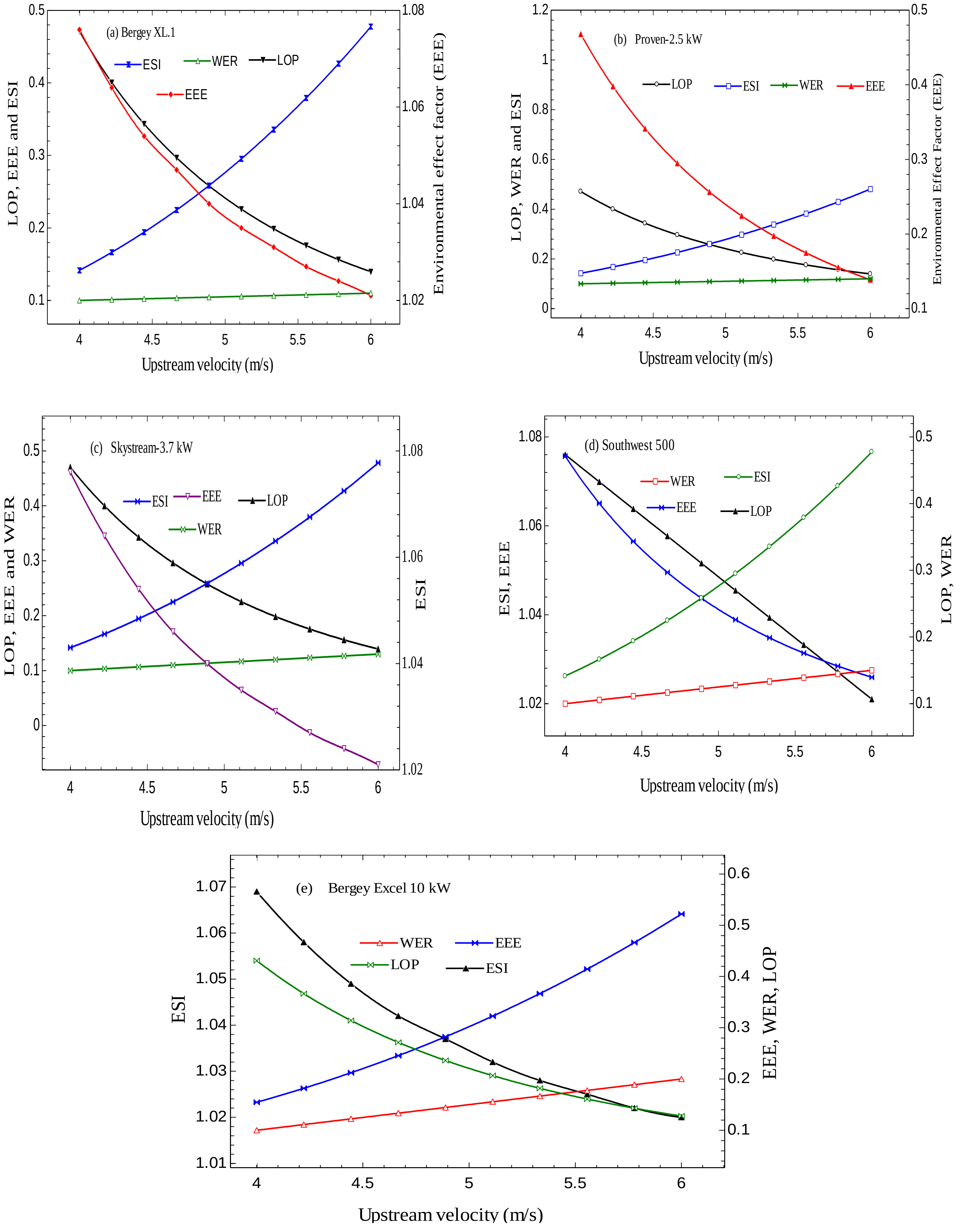


Figure 4. Variations in sustainability indicators with upstream velocity

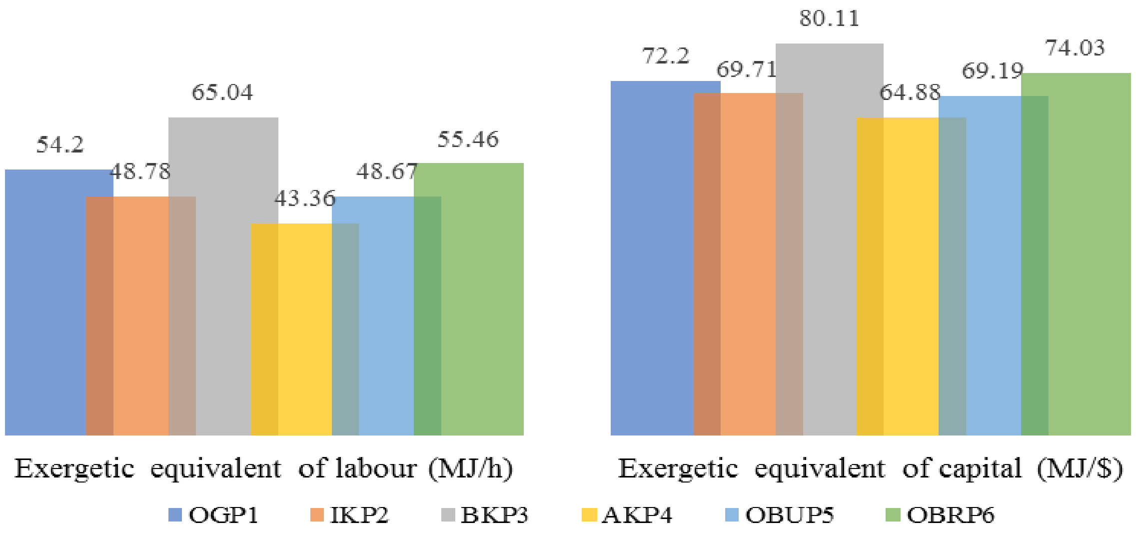


Figure 5. Exergetic equivalent of labour and capital

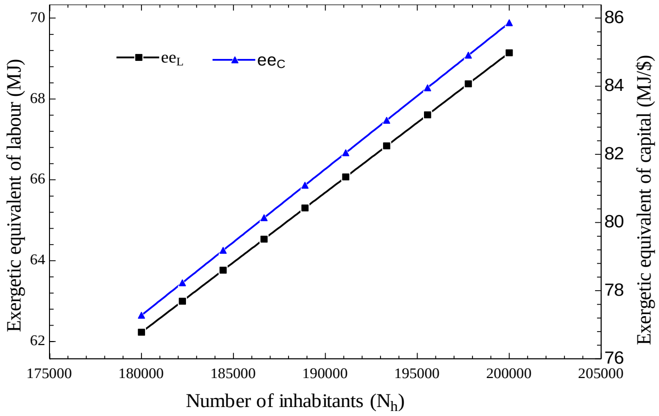


Figure 6. Variations ee_L and ee_C with the number of inhabitants

The cost of kWh electricity generated by a WECS is obtained by

$$COE = \frac{GPV(CA)}{E_T} = \frac{C_{iv}}{E_T n}\left(1 + h\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right]\right) \tag{12}$$

Where h is C_{om} expressed as a percentage of C_{iv} $\left(\frac{C_{om}}{C_{iv}} = h\ \%\right)$.

Using data from Table 4 and economic assumptions, the energy cost (COE) per kWh for various WECS across locations was calculated (Figure 7). COE ranges from 0.063 $/kWh to 0.181 $/kWh. In OGP1 (Figure 7a), the lowest COE is 0.114 $/kWh for Bergey XL.1, while Skystream 3.7 kW has the highest at 0.1743 $/kWh. Differences in COE between WECSs at OGP1 are 0.019 $/kWh (14.29%) between Bergey XL.1 and Bergey Excel 10 kW, and 0.040 $/kWh (25.97%) between Bergey XL.1 and Bergey Excel 10 kW. In IKP2 (Figure 7b), Bergey XL.1 and Southwest 500 have the lowest COE (0.0082 $/kWh, 0.1215 $/kWh). BKP3 (Figure 7c) shows a COE range of 0.0634–0.172 $/kWh, with the highest for Bergey XL.1. AKP4 (Figure 7d) and OBUP5 (Figure 7e) show promising COEs for certain WECSs. BRP6 shows high COEs for all WECS except Bergey XL.1 (Figure 7f).

3.8 Electricity Cost and WECS suitability for location investment

The current electricity cost in Nigeria is ₦68/kWh, with a proposed tariff increase for band A and B users to ₦225/kWh (0.134 USD). Based on this, the Bergey XL.1 is suitable for investment in OGP1, IKP2, OBUP5, and OBRP6, with COE of ₦178.1/kWh, ₦128.1/kWh, ₦98.25/kWh, and ₦110.9/kWh, respectively, (Figure 8). Proven-2.5 kW is suitable in all locations except OBRP6, where its COE is ₦257/kWh, 12.45% higher than ₦225/kWh. Skystream 3.7 kW is ideal for IKP2, BKP3, and AKP4. Southwest 500 and Bergey Excel 10 kW are suitable for other locations. Further economic analysis is recommended for investment decisions.

3.9 Estimation of the payback period (PBP)

The payback period (PBP) is when a project convalesces its preliminary investment cost without considering its salvage value and time value of money [43]. Every investor expects a shorter payback time for any investment, consequently making payback time an indispensable economic decision factor.

$$\text{PBP} = \text{Initial investment} / \text{Estimated EUA} \tag{13}$$

At PBP, the accrued net present value of costs (PVC) and benefits (PVB) are equal, as determined from Eqs (13) and (14).

$$\text{PVB} = \text{EUAB}\left[\frac{(1+\text{i})^{\text{n}} - 1}{\text{i}(1+\text{i})^{\text{n}}}\right] \tag{14}$$

$$PVC = \left[1 + C_{om}\left(\frac{1+i}{r-i}\right) \times \left[1 - \left(\frac{1+i}{1+r}\right)^n\right] - S\left(\frac{1+i}{1+r}\right)^n\right] \tag{15}$$

Figures 9-11 presents the payback period (PBP) for selected WECSs at three locations: OGP1, IKP2, and BKP3, demonstrating the viability of wind projects. At OGP1, the PBP for Proven-2.5 kW, Skystream 3.7 kW, Southwest 500, and Bergey Excel 10 kW are 4.2, 3.5, 3.2, and 4 years, respectively. At IKP2, the PBP ranges from 3 to 3.6 years. At BKP3, Bergey Excel 10 kW has the longest PBP of 5.6 years, followed by Southwest 500 at 3.5 years. The study indicates promising investment potential.

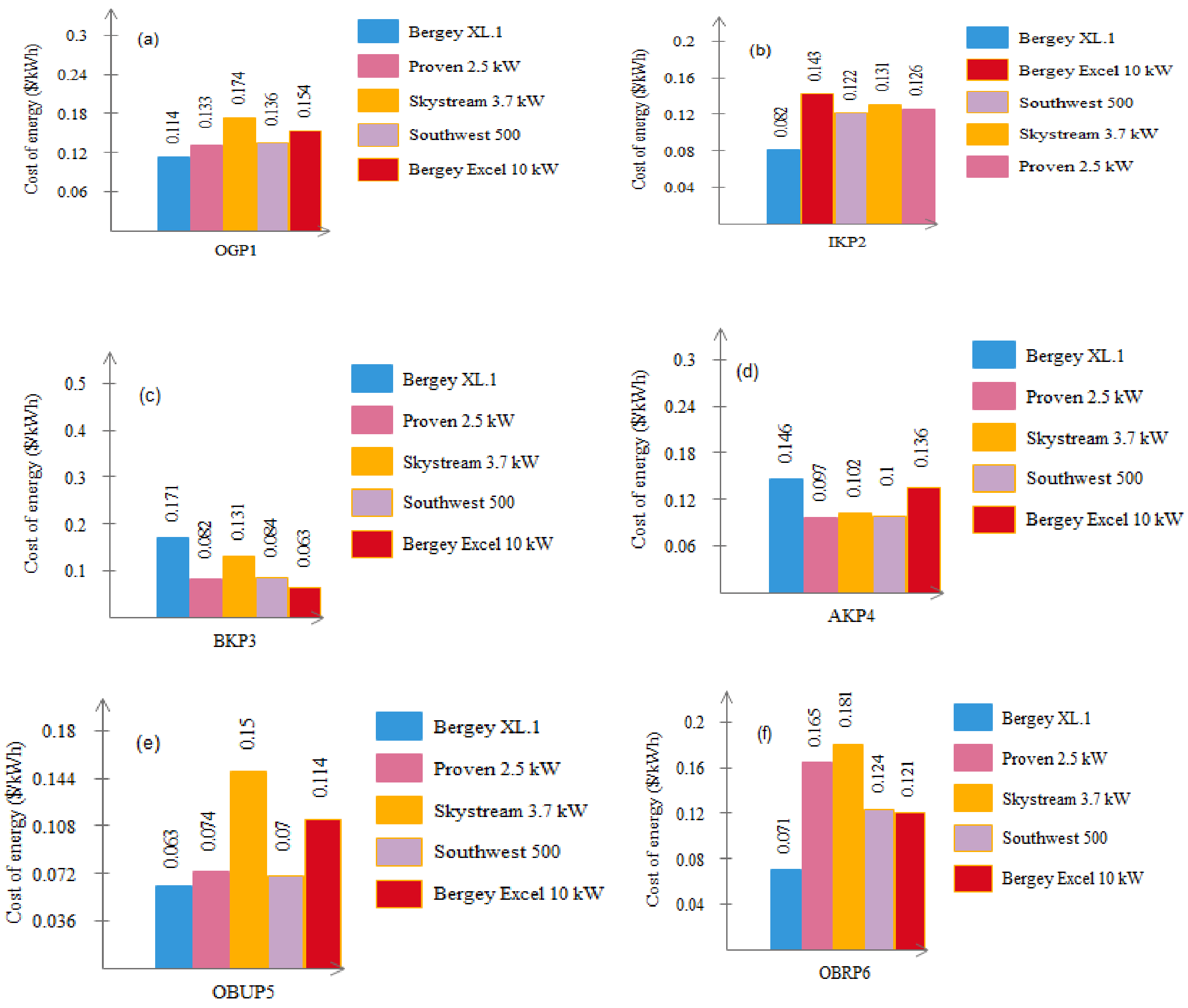


Figure 7. Cost of energy per kW for all WECS and locations (a) OGP1, (b) IKP2, (c) BKP3, (d) AKP4, and (OBUP5) and (f) OBRP6

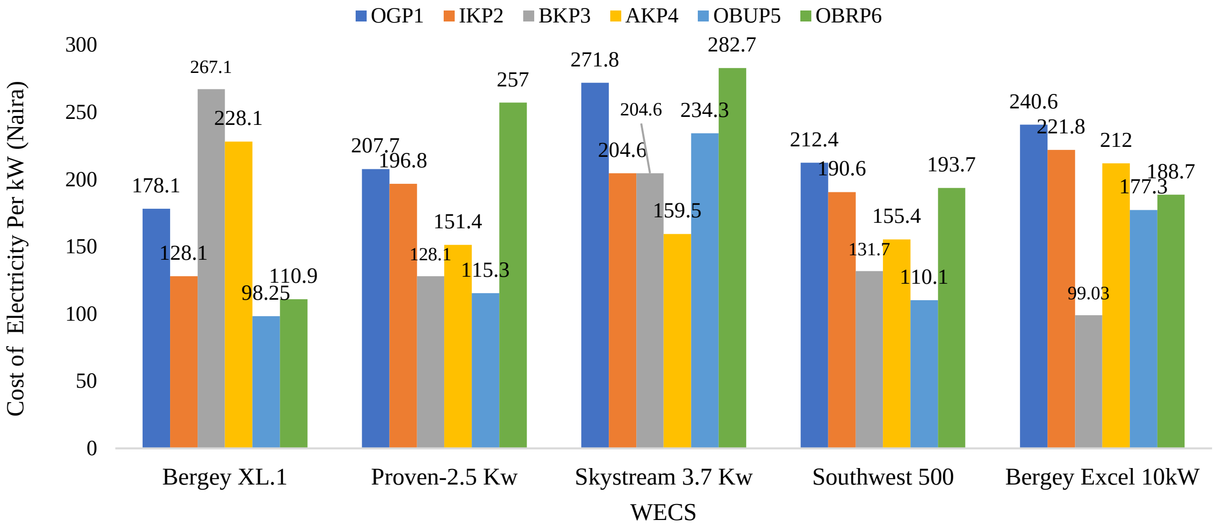


Figure 8. Electricity cost per kW in (Naira) for the WECSs in OGP1, IKP2, BKP3, AKP4, OBUP5 and OBRP6

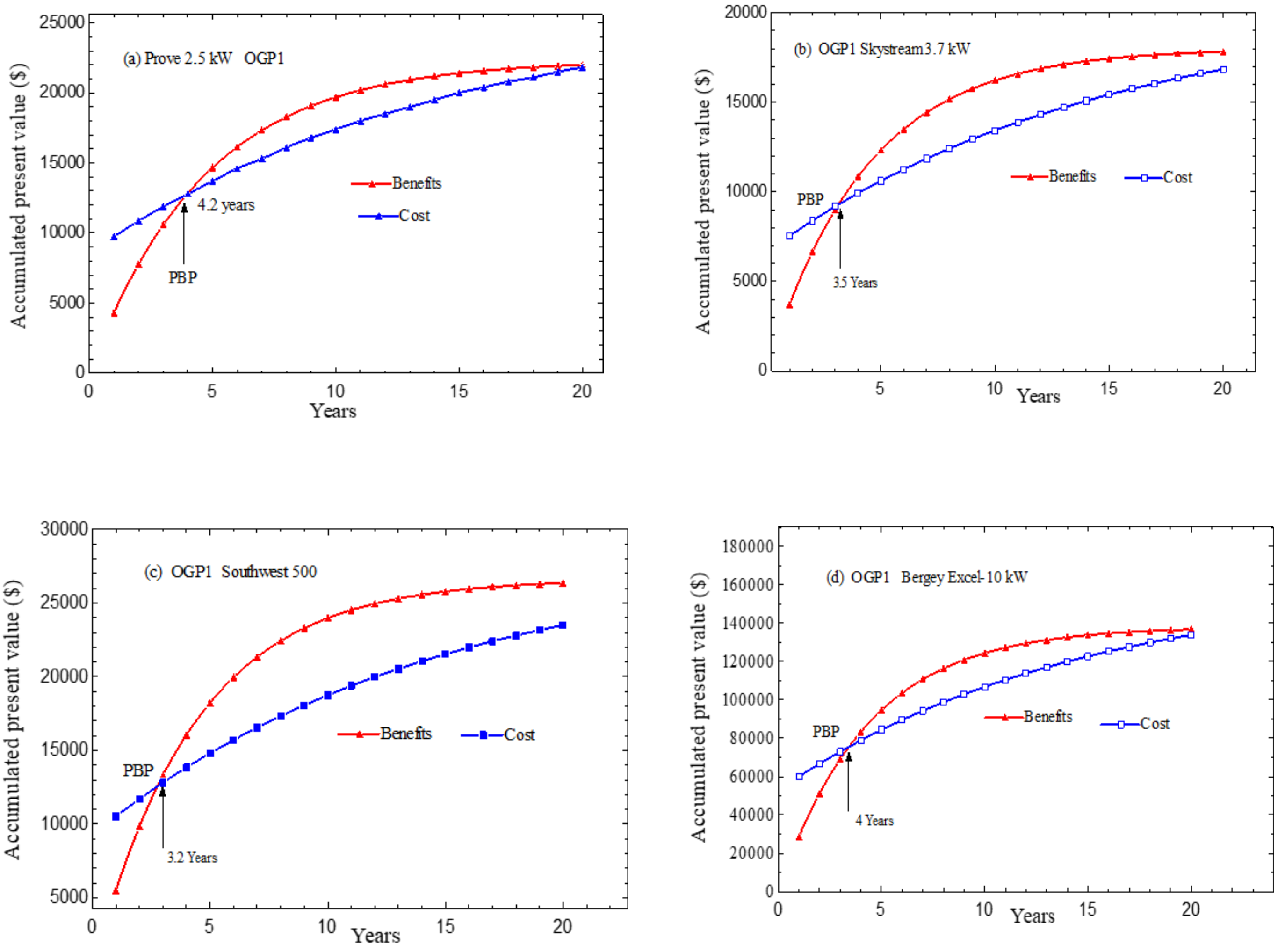
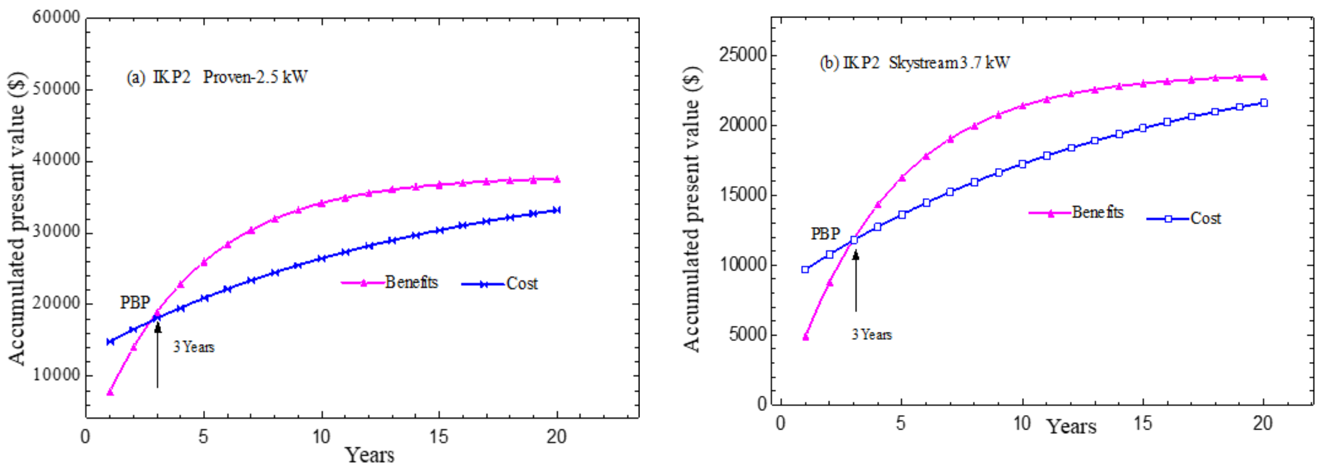


Figure 9. Economic payback of investment in OGP1 for WECS (a) Proven-2.5 kW, (b) Skystream 3.7 kW, (c) Southwest 500, and (d) Bergey Excel 10 kW



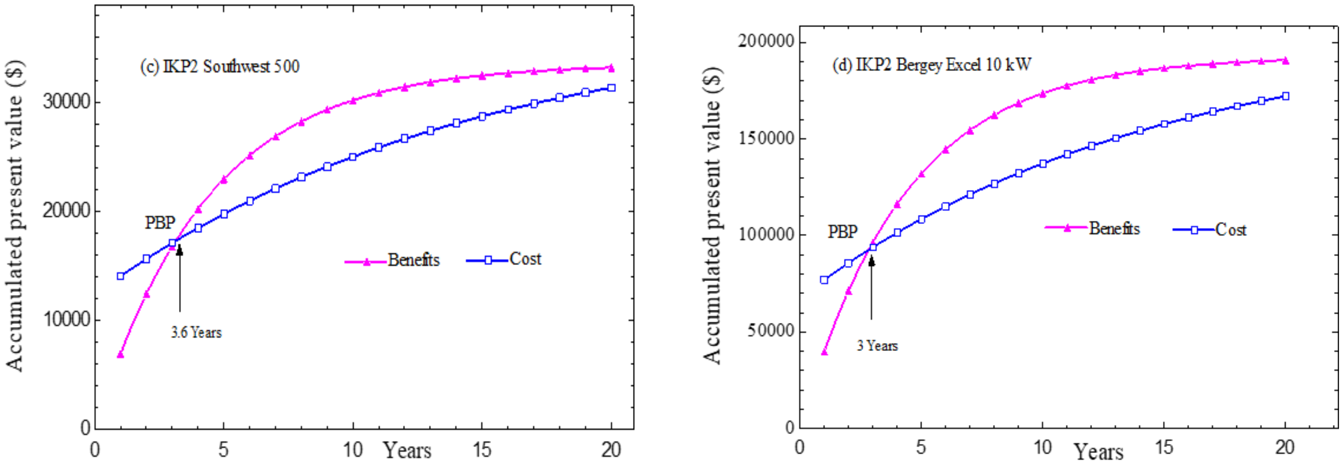


Figure 10. Economic payback of investment in IKP2 for WECS (a) Proven-2.5 kW, (b) Skystream 3.7 kW, (c) Southwest 500, and (d) Bergey Excel 10 kW

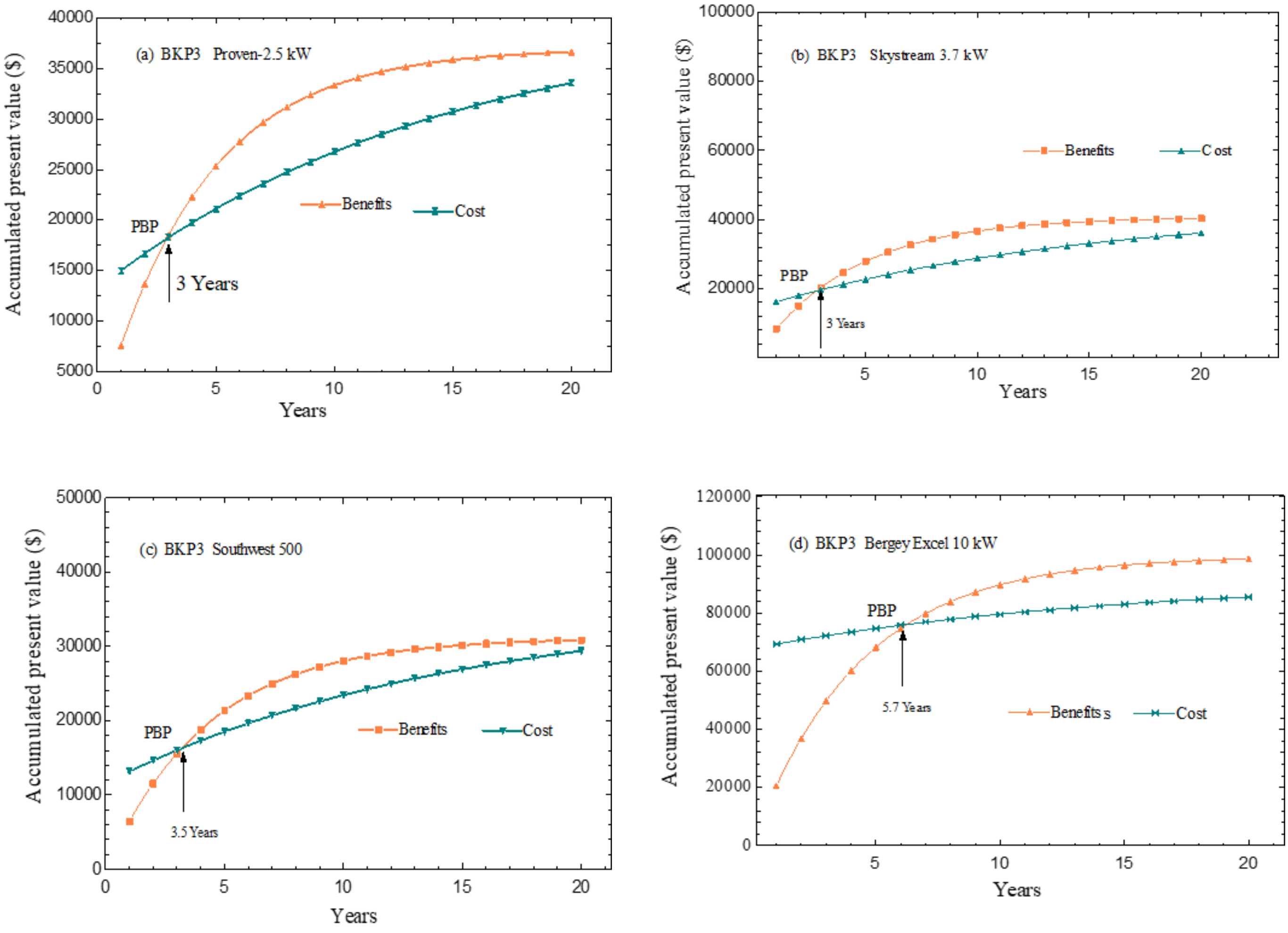


Figure 11. Economic payback of investment in BKP3 for WECS (a) Proven-2.5 kW, (b) Skystream 3.7 kW, (c) Southwest 500 and (d) Bergey Excel 10 kW

4. Conclusion

This study evaluated the performance and sustainability of Wind Energy Conversion Systems (WECS) using standard and extended exergy accounting measures across six different locations and WECS sizes. Wind velocities ranged from 3 to 3.5 m/s, with probabilities of occurrence at various sites: OGP1 (27.56%), IKP2 (38.26%), BKP3 (13.75%), AKP4 (18.21%), OBUP5 (42.36%), and BRP6 (6.59%). Monthly and annual wind power density (PD) values ranged from 6.8 to 102.90 W/m^2, and energy density (ED) from 4.49 to 85.58 kWh/m^2. Annual PD and ED ranged from 48.31 to 85.58 W/m^2/year and 151.50 to 747.39 kWh/m^2/year. The study analyzed small WECS (2.5–10 kW), yielding between 56.79 and 24,524.26 kWh/month and 1,458.99 to 43,921.82 kWh/year. The lowest exergy destruction (ExD) was observed with the Bergey XL.1, ranging from 1.351×10^6 to 5.67×10^6 MJ, with exergy efficiencies between 2.88% and 5.97%. COE ranged from \$0.063 to \$0.181 per kWh across locations and WECS. The low values based on extended exergy accounting (EAA) are attributed to excluding externalities in conventional methods. The EEA method effectively provided realistic data to guide investment and policy decisions in small WECS development and investment.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically concerning authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere in any language.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the corresponding author.

Conflict of interest

The authors declare no potential conflict of interest.

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